Saskatchewan
Research Council

SIMULATION OF SPRING WHEAT YIELDS IN THE SASKATOON CROP DISTRICT 1960 TO 1984 USING THE CERES WHEAT GROWTH MODEL

by

Fei, Qing-Pei
Saskatchewan Research Council
30 Campus Drive
Saskatoon, Saskatchewan
S7N 0X1

and

Earle A. Ripley
Department of Crop Science and Plant Ecology
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 0W0

SRC Technical Report No. 178

Publication E-906-46-B-85 December, 1985

SIMULATION OF SPRING WHEAT YIELDS IN THE SASKATOON CROP DISTRICT 1960 TO 1984 USING THE CERES WHEAT GROWTH MODEL

by

Fei, Qing-Pei
Saskatchewan Research Council
30 Campus Drive
Saskatoon, Saskatchewan
S7N 0X1

and

Earle A. Ripley
Department of Crop Science and Plant Ecology
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 0W0

SRC Technical Report No. 178

SRC Publication No. E-906-46-B-85 December, 1985

PREFACE

Mr. Fei, Qing-Pei came to the Saskatchewan Research Council from the Meteorological Bureau of Jiangsu Province, China, under the auspices of the Canada-China Human Development Training Programme of the World University Service of Canada. This Programme is aimed at upgrading the qualifications of Chinese professionals through in-job training at Canadian institutions.

Since his arrival, in May 1985, he has contributed substantially to many activities at the SRC and the University of Saskatchewan, by assisting in areas that might not otherwise have been explored. In many instances his efforts, particularly with regard to the Climatological Reference Station, have relieved work pressures on other staff, and his expertise and hardworking, compatible nature have enriched many of our programs. We wish to thank the WUSC for giving us the opportunity to work with Pei, and to express our appreciation for the work he has done for us.

The present research was carried out in cooperation with Professor Earle Ripley of the Department of Crop Science and Plant Ecology of the University of Saskatchewan. The goal was to adapt an existing wheat-growth model (CERES) to Saskatchewan conditions, and to assess its ability to simulate actual yields in a crop district over a 25-year period.

S.R. Shewchuk
Manager, Atmospheric Processes
Research Group
Environment Division, SRC

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
2. DESCRIPTION OF THE CERES MODEL	3
Program Structure	4
3. INPUT DATA DESCRIPTION	7
Irrigation	7
Crop Genotype Information	8
Soil Moisture Data	11
Weather Data	14
Daily Solar Radiation Data	16
Daily Temperature Data	16
Daily Precipitation Data	16
4. RESULTS AND DISCUSSION	18
Sensitivity Analysis	18
World-Wide Test Runs	20
Saskatoon Study	21
5. CONCLUSION	25
6. LITERATURE CITED	26
7. LIST OF TABLES	ii
8. LIST OF FIGURES	iii
9. LIST OF APPENDICES	iv

LIST OF TABLES

Table		Page
1	Seeding Dates and Pre-Seeding Weather Data	28
2	Cansis: Saskatchewan Soil Profile Data	29
3	Soil Water Content at End of April	30
4	Soil-Water Content Derived from Winter Precipitation	31
5	Soil-Layer Thickness and Root Growth Weighting Factors . . .	32
6	Empirical Formulae for Calculating Daily Solar Radiation . .	33
7	Comparison of Actual and Simulated HR Spring Wheat Yields (kg/ha)	34

LIST OF FIGURES

Figure		Page
1	Input/Output Features of the CERES Wheat Model	35
2	CERES Wheat Model	36
3	Saskatchewan - Crop District 6	37
4	Root Growth Distribution	38
5	Modelled vs Measured Yield	39
6	Saskatoon Wheat Yields - 1960 to 1984	40
7	Saskatchewan Wheat Yields: 1916 - 1984	41

LIST OF APPENDICES

Appendix		Page
A	1951-80 Average Daily Saskatoon Weather Data As Used in CERES Model	42
B	CERES Model - Soils data files for use with mean weather data	43
C	Input Format of Crop and Miscellaneous Parameter Data	44
D	Location: Saskatoon; Variety Number: 101	45
E	Plant Genetic Parameters	46
F	Crop Data Other than Genetic Required to Run or Validate Model =	47
G	Label Directory	48

1. INTRODUCTION

Many factors affect crop yields, some of which are under the farmer's control, and some of which are not. After choosing where, when and how his crop is planted, the farmer is at the mercy of the weather it will experience before it matures, and the pests and diseases that may reduce the quantity or quality of the final yield.

In spite of agriculture's great technological advances in recent decades, weather remains as the major (largely) uncontrollable factor affecting crop yield on the Canadian Prairies. Although experience has taught farmers that inadequate soil moisture is probably the main weather-related limitation to crop growth, the complex nature of weather, and of the interactions between it and soil moisture, make it very difficult to predict yield on the basis of simple climatological data.

While it is true that a number of successful empirical models have been built relating crop yields to monthly values of precipitation and temperature (for example, see Baier, 1977), these have had only limited applicability outside of the geographical area and period of time for which they were derived. In addition, these types of models have not usually been capable of providing any indication of what the yields might have been if some of the growing conditions had been different. For example, what yield might have resulted if winter snow-trapping had been employed; or if the crop had been planted earlier or later than it was.

A more useful type of model divides the crop growth process into its many components and attempt to simulate each one of these, finally combining the parts into an integrated whole. The complexity of such an

approach requires a great deal of knowledge about the processes of crop growth and development and the use of a computer to carry out the integration. While one might expect the increase in complexity would result in more accurate yield simulation, this is usually not the case, and the simpler statistically-based models often remain superior in that regard. However, only the process-based models are capable of telling us which crop, soil and weather parameters will have the greatest effect on growth, development and water use, and are able to provide guidance for the breeding of new varieties and the development of more-productive management practices.

Of the numerous process-based wheat growth and development models that have been developed in recent years, that of Ritchie and Otter (1985) is one with the most general applicability. It has been tested with a large amount of data from around the world and has also been used successfully in southern Saskatchewan (Jame, personal communication). With a view to developing the model for use as an operational tool, it was decided to initially test it with 25 years of historical data (Saskatchewan Agriculture, 1985) for the Saskatoon Crop District (6B).

2. DESCRIPTION OF THE CERES MODEL

The CERES model (Ritchie and Otter, 1985) was developed by a team of crop scientists at the USDA Grassland, Soil and Water Research Laboratory in Temple, Texas. It was designed to simulate the phenological development, growth and yield of a wheat crop in response to changes in weather, soil moisture and genotype under a wide range of climatic conditions.

The model was written in the FORTRAN language and was originally implemented on a mainframe computer. It has been adapted for an MSDOS microcomputer and compiled using the Microsoft FORTRAN compiler, version 3.2. The source code comprises about 1180 lines of code and occupies about 40 Kbytes of storage space. After compilation and link editing, the run file has a size of about 71. Time required for compilation is about 9 minutes plus about 2 minutes for link editing. Run times average about one minute per year (spring wheat), but are closely related to the size and ease of access of the weather and soils data files.

The model operates on a daily time step and requires the following input data (Fig. 1):

- daily weather data: maximum and minimum temperatures, precipitation and solar radiation (see Appendix A);
- soil data: mainly upper and lower limits of water availability and initial soil moisture (see Appendix B);
- crop data: genotype-specific coefficients describing temperature and photoperiod response and dry matter partitioning (see Appendix C);
- irrigation data (if used).

The main output routine prints the date of occurrence of each phenological stage, together with the biomass, leaf area index and cumulative degree-days, soil water content and soil water deficit and

precipitation, evaporation and transpiration at each stage. Also provided are number of vernalization days, numbers of tillers and grains per square metre, mean grain weight and final yield.

There are also optional outputs of detailed soil moisture and water balance information and of detailed growth information. Either, or both, of these may be printed out at any desired time interval. The former includes soil, plant, total and potential evaporation, precipitation, runoff and drainage, and the water contents of each soil layer, as well as the total available soil water. The latter gives the biomass; leaf area index; specific leaf weight; root, stem, grain and leaf weights; and rooting depth and root lengths in each soil layer.

A sample of the program output is shown in Appendix D.

Program Structure:

The MAIN program segment is augmented by 12 subroutines (Fig. 2). The function of each subroutine is as follows:

- PROGRI: reads in crop and other parameter data and initializes several variables.
- SOILRI: reads in and initializes soil variables.
- WATBAL: calculates runoff, infiltration, soil and plant evaporation, drainage and changes in soil water content of each layer.
- PHENOL: computes phenological stage.
- PHASEI: initializes variables at the beginning of each phenological stage.
- GROSUB: this growth subroutine calculates the daily biomass production and distributes it to the growing plant parts.
- LEAF: called from GROSUB during stages 1 and 2 to calculate leaf area growth from relative extension growth.

- WRITE: writes output of general weather, water and crop growth and development data.

- COLD: called from PHENOL, during stages 1 and 9 only to calculate vernalization days and tiller kill due to low temperatures.

- OUTWA: called from PROGRI and WRITE, at the interval specified in the input parameter data (KOUTWA), to output detailed soil water data.

- OUTGR: called by PROGRI and WRITE, at the interval specified in the output parameter data (KOUTGR), to output detailed growth data.

- CALDAT: called by several routines, calculates the calendar date corresponding to a Julian date.

After opening input and output files (MAIN), PROGRI is called to read in the crop and control data for the run. A number of variables are initialized, such as setting the degree-day base temperature at 2°C and the growth stage at 7. The location and variety, and crop and miscellaneous data are printed out and OUTWA and OUTGR called to initialize water balance and growth calculations and write them to a disk file (if specified by KOUTWA and KOUTGR).

Next, SOILRI is called to read in the appropriate soil data for the year specified. These data are printed out for reference and a number of soil variables are initialized. Control is returned to MAIN which then finds and reads in a day's weather data for the appropriate year.

Subroutine WATBAL is called next, initiating water-balance calculations. This subroutine calculates runoff and drainage, potential evapotranspiration, soil evaporation and crop transpiration, root growth and changes in the soil-water profile.

Subroutine PHENOL (Appendix E) is then called if the date equals the date of sowing or if the growth stage is not equal to 7. Degree-

days are calculated using the base temperature appropriate to the particular growth stage (0°C for stages 1 to 4; 1°C for stages 5 and 6; and 2°C for stages 7 to 9). If the growth stage is 1 or 9, subroutine COLD is called from PHENOL and vernalization days or cold damage are calculated. Next, PHASE I is called to set the values of a number of variables relevant to the particular growth stage.

If the growth stage is between 1 and 5, subroutine GROSUB is called. Photosynthate is calculated from solar radiation and leaf area and partitioned to the various parts of the plant. For stages 1 and 2, LEAF is called to calculate leaf growth.

Next, subroutine WRITE is called to calculate average values of the water-balance terms for the period and to call OUTWA and OUTGR at the appropriate times to write the appropriate water-balance and growth data to disk.

The program then cycles back through MAIN to read another day's weather data and to proceed on through WATBAL, PHENOL, etc. as before, until crop maturity is reached. This completes a particular "run" and the program then looks for another crop data input "card" and, if present, begins a second "run".

3. INPUT DATA DESCRIPTION

Light, heat, moisture and carbon dioxide are essential to plant growth. Different combinations of these factors are required by different plant species. These factors are governed by climatic conditions and soil moisture. The importance of each factor differs among different plants. The changes of carbon dioxide content in the air is very small and may usually be ignored. The other three factors change markedly from day to day and from year to year, and have different effects on different crops.

The CERES wheat model is designed to run with inputs of soil, crop and weather data, and operates on a daily time step. Daily weather data are required, most of which are available from standard meteorological stations. In addition, initial soil moisture data are required for each layer of the soil. To run the model for past years may require some treatment of the original data. In cases where the required data are not available, they will be derived from others.

In order to simulate wheat growth in the Saskatoon Crop District, four groups of data are required by the model. They are irrigation, crop genotype information, soil water data and weather elements. The following describes the preparation of the input data.

Irrigation:

Water stress is one of the main factors limiting wheat growth. It may result in partial or total crop failure. For small areas, irrigation is feasible and promotes wheat growing greatly. The extent to which irrigation is used for growing wheat in the Saskatoon Crop District is negligible so it has not been considered in the following simulations.

Crop Genotype Information:

The CERES model is designed to simulate crop phenological development, growth and economic yield. Differences among wheat varieties result from differences in genotype-specific coefficients related to photoperiod, vernalization, temperature response, thermal time required for certain phenological events, and dry matter partitioning. The format of the spring wheat genetic parameters as used in this study are shown in Appendices C and E.

Appendix E explains the wheat genetic parameters. Those beginning with the letter P are characters of wheat with reference to photoperiod, vernalization and thermal time. Those beginning with the letter G describe the components of biomass used for calculating economic yields. Both genotype and environment affect phenological development. In the CERES model, phenological development is driven by accumulation of growing degree days (GDD). However, the effects of GDD on phenological development are modified by vernalization and photoperiod. As described earlier, the base temperature used in the model varies from 0 to 2°C. On this scale, total degree-day requirements for spring wheat maturity are about 1450.

The crop phenology component of the CERES model describes the changing allocation of dry matter accumulation among plant organs during the course of crop growth. The growth of spring wheat is divided into 9 phases (Appendix E) of which the growth phases are described as follows:

Wheat growth stages in CERES wheat model and plant parts growing during each stage:

No.	Stage	Plants Parts Growing
8	Sowing to germination	
9	Germination to emergence	roots, coleoptile
1	Emergence to terminal spikelet	roots, leaves
2	Terminal spikelet to end of vegetative growth	roots, leaves, stems
3	End of vegetative growth to end of pre-anthesis ear growth	roots, leaves, stems, ears
4	End of pre-anthesis ear growth to beginning of grain fill	roots, stems
5	Beginning of grain fill to maturity	roots, stems, grains

Some crop data other than genetic are required to run the model. They are depth of seeding, date of seeding and seeding density. Some notes relating to appropriate values for these parameters may be found in Appendix F.

In general, the deeper the seeding depth, the longer it takes the shoot to emerge. In climates with short growing seasons, this usually means reduced yields. Although different seeding depths might be used for the simulations, no information is available regarding actual seeding depths so it was decided to employ a constant value of 5 cm for the entire series of simulations.

As with seeding depth, the date of seeding changes widely from place to place. It depends on spring temperatures and soil moisture. For the Saskatoon Crop District, the average seeding date of each year

as published in Anonymous (1980, 1983, 1985) has been used. It is specified in terms of Julian date (see Table 1). The Julian date 134 is the mean date of seeding for use with mean weather data.

The Julian date was not available for several years. Accordingly, a relationship between it and spring weather was looked for as a means of estimating it when missing. Two regression equations were chosen. They are as follows:

$$y_1 = 123.9 - 0.563\ T, \qquad r = -0.79$$
$$y_2 = 121.7 + 0.129\ P, \qquad r = 0.51$$

Where y_1 and y_2 are Julian date; T is sum of monthly mean air temperatures from February through April and P is total precipitation from December through April. The correlation coefficients of -0.79 and 0.51 respectively, are both significant at the 1% level. The estimated seeding dates from the equation of temperatures are shown in Table 1. The standard error of the estimate is ±3.8 and the regression accounts for 62.4% of the variance. From the first equation above, the estimated seeding date for 1985 would be 133. These two equations indicate that early seeding dates are related to high springtime temperatures and low winter and spring precipitation. Because of its much higher correlation coefficient, the temperature relationship is used to fill in the few missing dates in this study.

Plant population is related to seeding density. The recommended rates for wheat are shown in Appendix F. It varies with soil types. For the prevailing soils of the Saskatoon crop district, a seeding density of between 200 and 300 per square metre is recommended. In the present study, it has been set at 250.

Appropriate values of the crop genetic parameters were chosen using information supplied by Wong (1985) and Baker (personal communication).

Soil Moisture Data:

The different soils of the Saskatoon Crop District differ in their ability to produce crops. Crop yields vary widely from one year or location to another. These yield variations reflect the different management practices followed by the farmer, the differences in weather, and in the soils on which the crops are grown. Despite management practices, the major factors which affect the productivity of the soil are weather, soil texture and soil position in relation to the landscape (i.e. knoll, midslope or depression). The effect of weather on wheat yields will be discussed later. The position of a soil in the landscape has a variable effect on productivity. Generally, yields are higher in the lower and midslope positions and are lower on the knolls. Because of the large-scale approach of the present simulations, however, slope has not been considered.

The effect of soil texture on crop yields is primarly related to moisture-holding capacity. Clay soils may store enough water to grow a crop with the need for very little additional rainfall, while sandy soils are able to store much less water. In the Saskatoon Crop District, six soil types have been chosen. Asquith is referred to as "light" or "coarse" texture (L) soil and has lowest moisture-holding capacity. Bradwell, Elstow and Weyburn are "medium" texture (M) soils of which the moisture-holding capacity lies between sand and clay. Sutherland and Sceptre are "heavy" or "fine" texture (H) soils and have highest moisture-holding capacity.

Soil moisture reserves provide an index of crop production potentials. The amount of initial soil water content affects the germination and early growth stages, especially in arid regions. In the CERES wheat

model, initial soil water content, as well as upper and lower limits of water availability, are needed. The format of the soil data file is shown in Appendix B. For each soil type, the same format is used. The definitions of the abbreviations in the soil data file are given in Appendix G.

Not all of the moisture stored in the soil at seeding time can be extracted by the wheat roots. LL is the lower limit of water content of the soil. When it is reached, the plants wilt and growth ceases. At the other extreme, SAT indicates the water content of soil after it has been saturated by a heavy rainfall or irrigation. After a few days, part of this water drains below the rooting depth and thus is lost to the plants. This latter amount of water held by the soil is known as the field capacity or drained upper limit water content (DUL, shown in Appendix B). Wheat can use only the water held between LL and DUL. SW is the initial water content before seeding and is between LL and DUL.

Appendix B shows the values of the soil input data for the "average" year (coded as 1999). Values for individual years were not available as measured data so that indirect estimation methods had to be used.

The upper and lower limits of soil water availability were determined by analysing actual soil profile data from the Canadian Soil Information System (De Jong, personal communication). Six soil types were investigated, ranging from sandy to heavy clay (Table 2). Between five and twelve profiles of each soil type were averaged and smoothed slightly to give the mean profile data shown in Table 2 and Appendix B. The distribution of light, medium and heavy texture soils in the Saskatoon Crop District is shown in Figure 3. Using a grid counting method,

it was found that the Crop District has 12% light soil cover, 7% heavy soil cover and the balance of medium texture. The results of the yield simulations will be combined later in this report using weighting based on this distribution.

The initial soil moisture contents (i.e. at the end of April each year) were determined using the Versatile Soil Moisture Budget of Dyer and Mack (1984). These data were available for the period 1960 to 1970 only for a number of light, medium and heavy texture soils (Table 3). These were averaged to produce estimates of initial soil water contents of these textures for the eleven years (Table 3). The assumed total depth of the soil was 120 cm.

To make up for the lack of soil moisture data after 1970, it was necessary to find a way to derive soil moisture for those years from the data already known. A linear regression was carried out between initial soil water content and the precipitation of September through April. The equations obtained are:

$$y_l = 0.0208 + 0.000198x, \qquad r_l = 0.770$$

$$y_m = 0.0031 + 0.000400x, \qquad r_m = 0.792$$

$$y_h = -0.0031 + 0.000481x, \qquad r_h = 0.792$$

Where x is precipitation from last September through April; y_l, y_m and y_h are water content of light, medium and heavy soil respectively. Derived soil water content and winter precipitation are shown in Table 4.

The plant root system forms part of the total biomass of the plant and acts to draw moisture and nutrients from the soil. The soil input data file requires estimates of root growth weighting factors (see Appendix B). The distribution of wheat roots in the soil profile is

defined by these factors, which are assigned to each soil layer. Actually, the amount of wheat roots decline exponentially with depth. Figure 4 shows the assumed curve of root growth distribution. The horizontal scale is the fraction of roots per cm of depth, and the vertical scale is the soil depth (cm). The area on the left side of the curve is root proportion. The total area is 1 (i.e. 100%). With the method of grid counting, the weighting factor can be calculated in any depth with any thickness. For instance, the thickness of second layer of Asquith is 12 cm, the area shadowed with oblique lines is about 20% of the total area. So, the root growth weighting factor is 0.200. Similar to the method mentioned above, other weighting factors are easy to calculate. For the six soil types and each soil layer, the root growth weighting factors are shown in Table 5.

All of the soil input parameters needed to run the model were entered into the appropriate input data file as shown in Appendix B.

Weather Data:

Weather is the most dynamic factor affecting agricultural production. Under natural conditions, the characteristics of soil and crop change only slowly over periods of many years so that the changes in their parameters are usually negligible. In contrast, weather commonly undergoes agriculturally-significant changes over very short periods of time. In some years, weather conditions favor crop growth and the crop yields increase. In other years, weather conditions do not match the phenological development of the crop, and crop growth and yield are adversely affected.

Heat, light and moisture are essential requisites of crop growth. Crops need light for photosynthesis. Growth stages are controlled by

photoperiod and also affected by thermal time. Precipitation is the main source of soil moisture. The amount of rainfall and its distribution in a growing season are of great importance to plant growth. In the CERES wheat model, weather inputs are daily maximum and minimum air temperatures, solar radiation and precipitation. The format of the weather input data file is shown in Appendix A.

The solar radiation is specified in MJ/m^2. Wheat converts part of this solar energy into chemical energy in a form used for dry matter production. In the CERES wheat model, the solar radiation input is used for calculating daily biomass production. It is limited to 10 MJ/m^2 if it exceeds that value. If the temperature deviates from the daytime optimum of 18°C, the effective transformation of solar radiation is reduced.

The mean temperature of each day is calculated from the maximum and minimum temperatures. In the CERES wheat model, the base temperature lies between 0°C and 2°C (see Appendix E). If the mean temperature is equal to or below the base temperature, the daily thermal time is 0. If the mean temperature is above a critical "optimum" temperature (29°C in wheat), the daily thermal time is reduced due to a high temperature stress.

In the CERES model, the soil water content in the profile is adjusted in response to precipitation, runoff, drainage, soil evaporation and plant transpiration.

Daily weather data from 1963 to present were taken from the records of the Climatological Reference Station (CRS) of the Saskatchewan Research Council (SRC). The SRC has operated its CRS since 1963. Earlier data came from the Weather Station of the University of

Saskachewan which was located nearby. The CRS is located north-east of the City of Saskatoon in the center of a large wheat-cropped area. There is little urban influence.

All weather elements are recorded at the CRS. Although there are some gaps in the records of certain elements, and some measurement units have been changed, it is possible to derive the rest of the data from the records observed and to convert all data into the metric system. CRS is located in the center of the east part of Crop District 6B. In modelling wheat growth of Crop District 6B, the weather data are considered to be representative of the entire District. The data used as model inputs are summarized below.

Daily Solar Radiation Data:

1976 - 1984, transcribed from the archives of solar radiation.

1974 - 1975, read from the hourly pyramometer records.

1973, read from recorder charts by means of a planimeter.

1960 - 1972, calculated from daily bright sunshine by use of an empirical formula, $R_c/R_a = b + a\ n/N$. (It will be discussed later).

Daily Temperature Data:

1977 - 1984, transcribed from the archives of the CRS.

1960 - 1976, transcribed from the archives of the CRS and converted from Fahrenheit to Celsius.

Daily Precipitation Data:

1980 - 1984, transcribed from the archives of CRS.

1960 - 1979, transcribed from the archives of CRS and converted from inches to millimetres.

Since solar radiation data were not available from 1960 to 1972, the values were calculated from daily bright sunshine by use of an

Angstrom-type empirical formula:

$$R_c/R_a = a + b\ n/N,$$

where R_c is the global solar radiation, R_a is the value of R_c for a completely transparent atmosphere (both in MJ/m^2); n is actual duration of bright sunshine, N is maximum possible bright sunshine for a cloudless day (both in hours); n/N is the ratio of actual/possible hours of sunshine.

Wheaton and Begrand (1985) calculated daily maximum possible bright sunshine in hours and solar radiation outside the atmosphere for Saskatoon. These data were used for the above calculations.

The 1980-84 global radiation data were used to establish values of the parameters a, and b in the above relationship. Linear regressions were carried out for each month of the growing season using daily data. The results are presented in Table 6. It may be noted that the correlation coefficients in all cases exceed 0.9 and that the variation from month to month is not large, with values of a and b averaging about 0.215 and 0.517 respectively. These may be compared with values in the literature which range from 0.18 to 0.31 and 0.49 to 0.64 respectively, and specifically with values for Matador, Saskatchewan of 0.27 and 0.50 reported by Ripley (1973).

In order to calculate an "average" weather file to use for model testing and sensitivity analyses, mean values of solar radiation, and maximum and minimum temperatures were extracted. Precipitation was allowed to fall once a week so as to have at least an essence of realism. The complete weather data file for this "average" year is shown in Appendix A.

4. RESULTS AND DISCUSSION

Sensitivity Analysis:

The sensitivity of the model to values of the various user-adjustable parameters was tested, using average weather data and medium-texture soil data. A range of possible values of each parameter, above and below that used in the Saskatoon simulations, was chosen and the appropriate runs of the model made.

Sensitivity Analysis For Average Weather Data and Bradwell Soil

Factor	Range		Yield Variation
SWCON	0.300 - 0.500		< 1%
U	6.000 - 8.000		low for dry soil; up to 5% for wet soil
SALB	0.120 - 0.140		+5%
CN2	50.000 - 70.000		no change
SW (init.)	6.200 - 8.800	cm	approx. doubling of yield
SDEPTH	5.000 - 10.000	cm	-7%
PLANTS	200.000 - 300.000		+15%
ISOW	125.000 - 145.000		approx. 20% decrease
PHINT	60.000 - 90.000		-25%
P1D	0.002 - 0.009		no change
P1V	0.002 - 0.004		+8%
P5	450.000 - 550.000		+10%
G2	15.000 - 45.000		+18%
G3	1.000 - 2.500		+5%
G4	0.500 - 1.500		-5%

It should be kept in mind that these results are for a year with "average" weather data and the responses may be quite different for any individual year, especially if it differs very much from average. The runoff controlling parameter CN2, for example, only becomes important when unusually heavy rainfall occurs.

The factor controlling soil water drainage, SWCON, has a negligible effect on yield in an average year (that is to say a year in which there is little drainage). Greater effects would likely be found following heavy rainfall events.

The upper limit for soil evaporation, U, depends on soil type and is most important during the early crop stages before there is much leaf growth. In addition to the direct effect on soil water content, variation in U will also affect soil water distribution and root growth.

Variation in soil-surface albedo changes the amount of energy available to evaporate moisture. The impact is greater, of course, when the soil is bare and diminishes progressively as leaf area develops.

The runoff parameter, CN2, has its greatest impact when rainfall is heavy. Thus, under the average weather conditions no effect is noticed.

Initial soil moisture is the factor with the greatest impact, especially in a dry year. The model indicates a yield increase of about 1500 kg/ha for an additional 2.6 cm of water in the initial soil profile (distributed uniformly with depth). This is considerably greater than most "rules-of-thumb" which suggest yield response to water of between 50 and 100 kg/ha per cm of water. This over sensitivity to soil water is possibly related to inadequate root growth in the model and will be discussed later with the results of the Saskatoon study.

Date, depth and density of sowing all may have significant effects on final yield. As long as moisture is not too severely limited, the model shows an increase in yield with seeding density of about 30% (i.e a 10% increase in seeding density will result in a 3% increase in yield). The effect of seeding depth is related to moisture availability and, in the "average" year, increasing planting depth reduces yield

slightly. Date of sowing can, of course, be very important, and each year will have its own optimum value which is best chosen, unfortunately, in retrospect. For average weather, delaying planting from May 5 to May 25 reduces model yield 20%.

The phyllochron interval, PHINT, specifies the rate of development during growth stages 2 and 3 (Appendix E). Increasing the value of PHINT increases the length of the growing period and may lead to an increase in yield if sufficient moisture is available, or a decrease if not. The latter situation was found for the "average" year.

Only a slight response was noted to variation in the vernalization factor and none to changes in the day-length factor. P2 and P3 are tied to PHINT in the model and cannot be varied independently. P4 is a variable parameter specifying the duration of the grain-fill phase in degree-days. As might be expected, yield responds almost linearly to changes in P5.

Of the genetic growth parameters, G1 and G5 are set internally at 1.0 so were not varied. There was a considerable yield response to G2, but almost negligible responses to G3 and G4 for the "average" weather situation.

World-Wide Test Runs:

To provide an indication of how well the model performs in other wheat-growing areas of the world, ninety-nine test results from sites around the world (Jones et al, 1983) were plotted and correlation coefficient and regression lines calculated (Fig. 5). Otter and Ritchie (1985) used a larger test sample (245 crop years) and found a correlation coefficient of 0.81. In general, these results show underestimation of yields by the model particularly at the high end of the range.

Since other factors that might reduce yield (such as nutrient limitations, soil water-logging, disease, hail damage, etc.) are not included in the model, one might have expected the model to err on the high side.

Saskatoon Study:

The results of the simulation runs for the Saskatoon Crop District for the years 1960 to 1984 are shown in Table 7 and Figure 6A. The simulated yields are shown for each of the main soil types in the District, together with a composite yield, obtained as a weighted mean based on the relative cropped areas of each soil type. It may be noted that on average the simulated yield (composite) for the period exceeded the actual by more than 50% and the model responses to both positive and negative departures from the mean were more extreme than those found in the actual yield data. That is, in low-yield years, the model underestimated yields, while in high-yield years the model over-estimated yields.

Part of the reason for the disagreement undoubtedly lies in the fact that the model simulates only the response to weather and ignores other factors such as nutrition, disease and insects. In particular, no account is taken in the model of possible increases in yield due to use of higher-yielding varieties, greater fertilizer applications or improved agronomic practices over the 25-year period. It is quite likely that technology has been responsible for a general trend of increasing yields from the 1940's to the present, seen for example in the plot of Provincial wheat yields shown in Figure 7. This figure shows an upward trend of about 24 kg/ha per year over the period of the present study.

It is likely also that variability is introduced by the estimation procedure used to arrive at initial soil moistures and by assuming the weather data at the SRC-CRS as representative of the entire Crop District. Other neglected factors include year-to-year variations in seeding depth and density, and in the distribution of land actually cropped in the different soil zones.

A statistical analysis of correlations between the several variables listed in Table 7 shows significant correlation between year and actual yield ($r = 0.556$), whereas no such relation could be found between year and simulated yield ($r = 0.043$). This indicates that the modelled values, dependent only on weather changes, exhibit no trends over the period, while the actual yields, dependent on other factors as well as weather, do exhibit a pronounced trend. Fitting a straight line to the actual yield data as a function of year produced the following relationship:

Actual yield = 32.1 * Year - 61661 kg/ha

It may be noted that this "technology trend" of 32 kg/ha per year is about a third higher than the Provincial average figure mentioned above.

The agreement between simulated and actual yields ($r = 0.610$) may be compared with the figure quoted earlier for results from many regions of the world. Whereas much of the earlier data was derived from individual plot studies, the current comparison deals with composite data from an entire Crop District having cropped area of over 2 million hectares and a diversity of soils and farming practices. It is difficult to assess the accuracy of the official estimates of "actual yield" for the District.

If we eliminate the "technology trend" from the actual yield data, i.e. by adding 32 kg/ha to the data for each year before 1984, the resulting figures (Table 7 and Figure 6B) represent the probable yields that would have resulted in previous years, if farmers had used 1984 technology. These "adjusted" yield data exhibit a higher degree of correlation with the simulated yields ($r = 0.70$) and the overall mean after adjustment is closer to the composite simulated figure (only 24% difference). The tendency of the model to over-estimate the higher yields and under-estimate the lower yields, is still there however, and we must look elsewhere for an explanation for this discrepancy.

Examination of the detailed water-balance and growth output tables, as for example in Appendix D, shows that the model is under-estimating the amount of root growth. Simulated values rarely exceed 10% of the total biomass. This is less than half of what is usually observed (e.g. Kramer, 1983), although literature values of root biomass vary widely (Walker, 1977).

If the model did under-estimate root growth, this would prevent the crop from extracting the moisture needed in drier years from the deeper layers of soil so that these would remain unexploited, and the simulated crop would suffer more from moisture stress than it should. This would restrict growth and the development of leaf area, and reduce yield. In wet years, however, the model would tend to produce excessive above-ground growth at the expense of root growth. This would not restrict water uptake since the roots would already be sufficient to exploit the adequate water supply, but the excess above-ground growth would lead to greater leaf-area development and higher yields. Also, because nutrition is not included in this version of the model, and thus

is assumed to be non-limiting, this may lead to an overestimation of yield in wetter years.

A possible reason why the model may fail to partition enough photosynthate to the root system may be that the more temperate varieties of wheat for which the model was developed may have more restricted root development at the lower temperatures experienced by the varieties grown in Saskatchewan.

5. CONCLUSION

After correction for a "technology trend" of 32 kg/ha per year, the CERES wheat model is able to simulate yields for the Saskatoon Crop District, during the period 1960-84, with a correlation coefficient of 0.70. Its main weakness, of overestimation in high-yield years and underestimation in low-yield years, appear to be at least partly related to an inadequate simulation of root growth in the model.

LITERATURE CITED

Anonymous (1978). The Soils of the Saskatoon Map Area 73-B, Saskatchewan Institute of Pedology.

Anonymous (1980). Agricultural Statistics 1979, Saskatchewan Agricultural Statistics and Public Information Branch, Regina, 112 pp.

Anonymous (1983). Agricultural Statistics 1982, Saskatchewan Agricultural Statistics and Public Information Branch, Regina, 132 pp.

Anonymous (1984). Guide to Farm Practices in Saskatchewan, University of Saskatchewan, Division of Extension and Community Relations, Saskatoon, 224 pp.

Anonymous (1985). Agricultural Statistics 1984, Saskatchewan Agricultural Statistics and Public Information Branch, Regina, 140 pp.

Austenson, H.M. (1979). Principles of agronomy with particular reference to Saskatchewan conditions, Crop Science Department, University of Saskatchewan, 70 pp.

Begrand, R.M. and E. Wheaton (1985). Sunrise, solar noon and sunset and Manitoba locations, Saskatchewan Research Council Publication.

Baier, W. (1977). Crop-weather models and their use in yield assessment. Tech. Note No. 151, World Meteorological Organization, Geneva, 48 pp.

Dyer, J.A. and A.R. Mack (1984). The versatile soil moisture budget-Version three, Tech. Bull. 1984-1E, Research Branch, Agriculture Canada, Ottawa, 24 pp. + apps.

Jones, C.A., J.T. Ritchie, J.R. Kiniery, D.C. Godwin and S.I. Otter (1983). The CERES wheat and maize models, unpublished typescript.

Kramer, P.J. (1983). Water Relations of Plants, Academic Press, New York, 496 pp.

Otter, S. and J.T. Ritchie (1985). Validation of the CERES-Wheat model in diverse environments, pp. 307-310 in: W. Day and R.K. Atkin (Eds.) Wheat Growth and Modelling, Plenum Press, New York.

Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass, Proc. Roy. Soc. (Lond.) A 193:120-145

Ripley, E.A. (1973). Description of site: II. Climatology of the Matador area, Technical Report No. 12, Matador Project, University of Saskatchewan, Saskatoon, 112 pp.

Ritchie, J.T. and S. Otter (1985). Description and performance of CERES-Wheat: a user-oriented wheat yield model, pp. 159-175 in: Willis, W.O. (Ed.) ARS Wheat Yield Project, ARS-38, USDA-ARS, Temple, TX.

Robertson, G.W. and D.A. Russelo (1968). Astrometeorological estimator Agrometeorological Section, Plant Research Institute, Research Branch, Canada Dept. of Agriculture.

Walker, G.K. (1977). Development of a wheat model for land evaluation, M.Sc. thesis, Dept. of Soil Science, University of Saskatchewan, Saskatoon, 195 pp.

Wong, L.S.L. (1985). Developmental analysis of time to maturity in six spring wheat crosses, PH.D. Thesis, Dept. of Crop Science and Plant Ecology, University of Saskatchewan, Saskatoon.

Table 1

Seeding Dates and Pre-Seeding Weather Data

Year	Seeding Date	Feb.- April Temperature	Dec. - April Precipitation	Estimated Date	Deviation
1960	135	-19.9	69.4	135	0
1961	134	-12.2	71.8	131	-3
1962	136	-23.7	67.6	137	1
1963	133	-12.3	87.1	131	-2
1964	134	-13.2	70.9	132	-2
1965	138	-28.5	79.3	140	2
1966	137	-22.5	84.5	137	0
1967	140	-30.1	97.8	141	1
1968	133	-10.7	97.6	130	-3
1969	132	-18.9	122.3	134	2
1970	139	-22.0	107.8	136	-3
1971	134	-18.7	102.4	134	0
1972	135	-22.8	121.6	137	2
1973	139	-12.8	113.8	131	-8
1974	146	-23.9	150.7	137	-9
1975	140	-30.0	110.2	141	1
1976	129	-11.4	117.3	130	1
1977	123	-1.3	61.5	125	2
1978	133	-15.3	100.3	133	0
1979	145	-34.9	123.6	144	-1
1980	126	-14.7	96.9	132	6
1981	130	-6.5	94.9	128	-2
1982	130	-22.0	72.2	136	6
1983	125	-14.0	112.9	132	7
1984	122	-2.0	46.3	125	3
1985	?	-15.9	119.3	(133)	?
Mean	134	-17.8	95.2	134	

Notes: The seeding dates are 'actual' values derived from Anonymous (1980 ; etc.). Highest correlations were found with the preceding February to April mean temperatures (deg C) and the December to April precipitation (mm). The highest correlation was with temperature and this relationship was used to calculate the estimated values and the deviations shown above.

Table 2

CANSIS: Saskatchewan Soil Profile Data

Soil	Code	# Prof.	**Layer #1**			**Layer #2**			**Layer #3**			**Layer #4**			**Layer #5**		
			cm	LL	UL	cm	LL	UL	cm	LL	UL	cm	LL	UL	cm	LL	UL
Asquith	A	6	10	0.091	0.174	12	0.085	0.150	20	0.094	0.163	20	0.097	0.171	58	0.116	0.202
Bradwell	Br	8	15	0.170	0.290	25	0.160	0.280	53	0.170	0.290	13	0.186	0.325	14	0.206	0.361
Elstow	E	10	38	0.190	0.330	10	0.200	0.360	12	0.210	0.370	10	0.250	0.430	50	0.260	0.460
Weyburn	W	12	10	0.186	0.320	22	0.170	0.299	10	0.170	0.310	34	0.172	0.301	20	0.173	0.290
Sutherland	Su	5	27	0.320	0.500	10	0.340	0.550	20	0.330	0.550	25	0.350	0.570	30	0.360	0.580
Sceptre	Sc	7	7	0.410	0.610	20	0.430	0.670	23	0.430	0.690	20	0.450	0.730	50	0.470	0.750

Code: cm layer thickness
LL lower limit of soil moisture availability (volume fraction)
UL upper limit of soil moisture availability (volume fraction)

Table 3

Year	Soil Water Content at End of April (cm)																		Mean Initial SW (vol.frac.)			Sep-Apr Prec(mm)
	L	L	L	L	L	L	M	M	M	M	M	M	H	H	H	H	H	H	L	M	H	
1960	8.92	8.92	8.79	8.92	8.79	8.92	12.83	12.80	12.93	13.21	13.40	13.23	14.55	14.55	14.50	15.65	13.97	15.67	0.074	0.109	0.123	210
1961	5.72	4.98	4.98	5.72	7.04	7.04	5.64	7.37	7.65	7.52	5.59	7.67	6.25	8.38	8.41	8.59	6.20	8.46	0.049	0.058	0.064	94
1962	7.06	7.04	6.22	7.39	6.40	7.39	9.50	8.00	7.34	10.36	6.83	11.73	9.80	8.53	7.80	11.02	7.26	13.11	0.058	0.075	0.088	118
1963	5.77	5.21	5.18	5.84	5.38	5.41	5.84	6.35	5.97	7.19	5.64	6.38	6.30	6.81	6.40	7.77	6.12	7.09	0.046	0.052	0.056	124
1964	3.40	3.43	3.60	5.51	3.73	5.46	3.73	3.89	4.11	5.97	3.99	5.77	4.11	4.29	4.39	6.45	4.22	6.22	0.035	0.038	0.041	123
1965	4.65	5.03	5.66	5.80	6.99	6.43	5.31	5.21	7.67	5.84	5.92	6.86	5.64	5.46	8.05	6.10	6.30	7.24	0.047	0.051	0.054	157
1966	4.29	4.29	5.54	6.55	5.82	6.55	4.60	4.65	6.45	7.04	5.79	7.01	4.90	5.05	6.55	7.49	5.07	7.42	0.046	0.049	0.052	135
1967	6.12	4.50	4.57	6.32	5.03	5.00	4.03	6.30	5.59	6.93	5.05	5.46	5.13	6.30	5.94	7.04	5.33	5.79	0.044	0.047	0.049	140
1968	5.94	5.94	5.04	6.10	5.09	6.07	6.43	8.20	6.43	8.43	6.25	6.60	6.65	8.56	6.63	8.04	6.40	6.00	0.050	0.059	0.061	174
1969	6.06	6.70	6.70	6.06	6.03	6.03	9.93	10.90	11.15	10.92	9.93	10.90	11.20	12.52	13.26	12.62	11.20	13.26	0.057	0.009	0.103	194
1970		9.07	9.07		9.07	9.07	12.42		13.61		13.31	13.20	13.07		15.02		15.27	15.24	0.076	0.110	0.125	259
																	Average		0.052	0.066	0.073	

Table 4

Soil-Water Content Derived from Winter Precipitation
(volume fraction)

Year	Soil Texture: Light	Medium	Heavy	Sep.-Apr. Prec. (mm)
1971	0.052	0.066	0.073	158
1972	0.052	0.065	0.072	156
1973	0.050	0.061	0.067	146
1974	0.068	0.099	0.112	239
1975	0.051	0.063	0.069	150
1976	0.054	0.069	0.077	166
1977	0.037	0.036	0.037	83
1978	0.054	0.069	0.076	165
1979	0.067	0.097	0.110	235
1980	0.051	0.063	0.069	150
1981	0.053	0.068	0.075	162
1982	0.047	0.057	0.061	134
1983	0.059	0.081	0.091	194
1984	0.049	0.060	0.065	143
1985	0.072	0.106	0.120	256

Table 5

Soil-Layer Thickness and Root Growth Weighting Factors

Asquith		Bradwell		Elstow		Weyburn		Sutherlan		Sceptre	
T	WR	T	WR	T	WR	T	WR	T	WR	T	WR
10	0.400	15	0.446	38	0.714	18	0.536	27	0.634	7	0.268
12	0.200	25	0.304	10	0.089	22	0.250	18	0.161	20	0.375
20	0.200	53	0.214	12	0.054	18	0.107	20	0.089	23	0.179
20	0.100	13	0.018	10	0.036	34	0.089	25	0.071	20	0.071
58	0.100	14	0.018	50	0.107	28	0.018	30	0.045	50	0.107

Where: T is the layer thickness in cm, and
WR is the root growth weighting factor.

Table 6

Empirical Formulae for Calculating Daily Solar Radiation

Month	Formula	r	N
May	Rc = Ra (0.227 + 0.495 n/N)	0.936	155
June	Rc = Ra (0.215 + 0.516 n/N)	0.918	150
July	Rc = Ra (0.217 + 0.507 n/N)	0.922	155
August	Rc = Ra (0.199 + 0.495 n/N)	0.909	155
September	Rc = Ra (0.216 + 0.571 n/N)	0.958	150

Where:
r is the correlation coefficient and N the number of samples.

Table 7

Comparison of Actual and Simulated HR Spring Wheat Yields (kg/ha)
Crop District 6B ---- for period 1960 to 1984

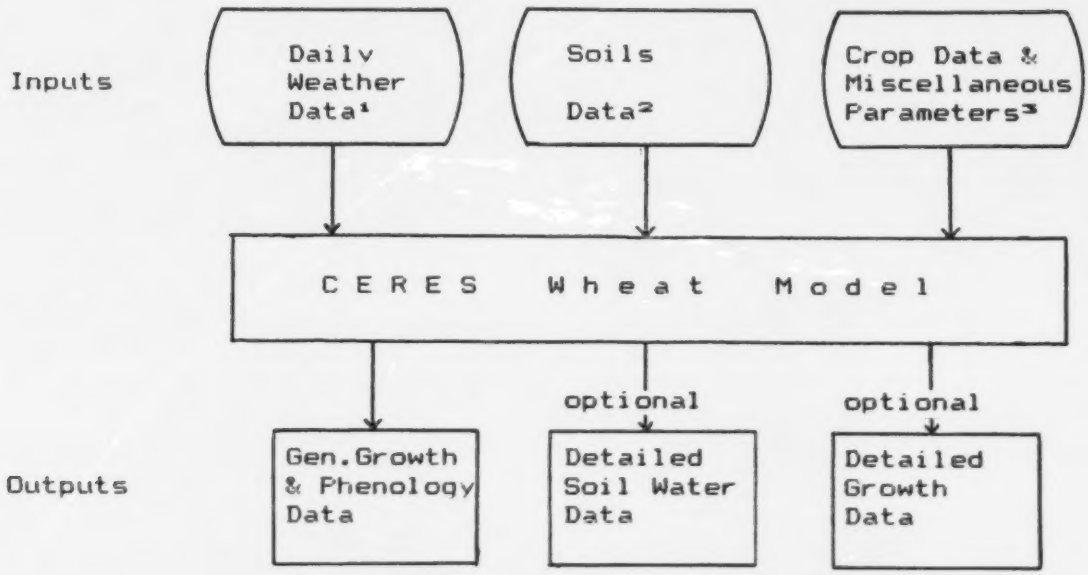
Year	Seed.Date	Actual	Asquith	Bradwell	Elstow	Weyburn	Suther.	Sceptre	Composite	Actual adjusted to 1984
1960	135	1485	1788	3685	3547	3428	4363	4571	3384	2255
1961	134	497	186	282	232	289	489	787	259	1235
1962	136	863	1491	2126	2183	2054	2822	3247	2189	1569
1963	133	1660	2144	2637	3278	3211	3463	3195	2954	2333
1964	134	793	127	516	361	300	416	515	366	1434
1965	138	1324	713	2681	2760	3328	4262	4448	2758	1933
1966	137	1945	2591	3986	3973	3910	4355	4530	3827	2522
1967	140	1082	570	753	701	736	795	833	717	1627
1968	133	1567	1787	2230	2071	2128	2322	2822	2130	2088
1969	132	1727	1686	2522	2455	2383	3106	3131	2398	2208
1970	139	1898	1830	4047	4039	4452	4856	4877	4162	2347
1971	134	1984	2639	5489	6024	5770	6488	6530	5439	2401
1972	135	1583	1781	2601	2603	2518	3331	3348	2532	1968
1973	139	1586	1463	1888	1718	1782	2059	2361	1783	1939
1974	146	1601	3203	6318	6655	6488	6888	6927	6101	1922
1975	140	1702	2899	2443	2172	2285	2474	2939	2304	1991
1976	129	2075	2671	2105	3499	2951	4435	4810	2954	2332
1977	123	1928	1418	1791	1465	1733	1539	1789	1631	2144
1978	133	1818	827	1333	1241	1247	1799	2198	1271	2010
1979	145	1561	1121	2716	3038	2863	3918	4123	2742	1721
1980	126	1400	90	128	154	163	477	1140	188	1528
1981	130	1701	594	585	819	620	2048	2635	760	1797
1982	130	2260	3094	4944	5250	5047	5443	5589	4872	2324
1983	125	2055	2432	4205	4455	4486	4783	4886	4180	2087
1984	122	1373	787	942	861	863	1127	1380	982	1373
Means	134	1578	1562	2508	2654	2598	3122	3338	2589	1963

Correlation coefficients---	r
Year vs. actual	0.556
Year vs. composite modelled	0.843
Year vs. actual adjusted	-0.011
Composite modelled vs. actual	0.618
Composite modelled vs. adjusted actual	0.783

Regression line of actual yield on year ('technology trend')--

Actual yield = 32.1 Year - 61661

Figure 1. Input/Output Features of the CERES Wheat Model.



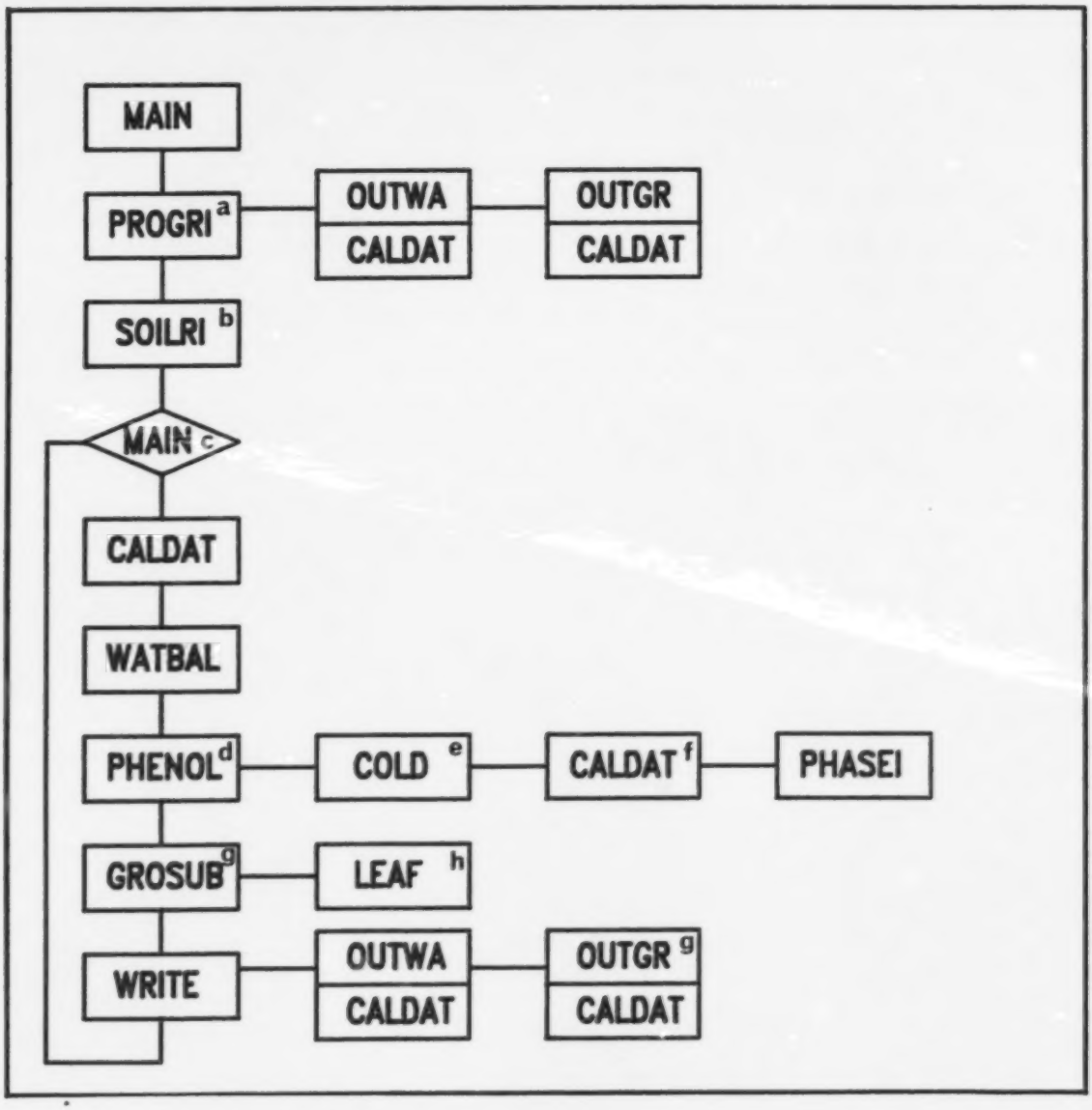
Notes: 1 -- The required input weather data comprise daily values of minimum and maximum temperatures, precipitation, and solar radiation, from 1 May to 30 September of each year (see Appendix A).

2 -- The required soils data comprise values of: soil albedo; the upper limit of soil evaporation; soil runoff and drainage parameters; and the lower and upper limits of soil water availability, and the saturated limit and initial (1 May) water content, of each soil layer (see Appendix B).

3 -- The required crop data comprise: genotype-specific parameters describing temperature and photoperiod response, and dry-matter partitioning; date, depth and density of sowing; and depth-weighted factors for root growth (these are actually included with the soils data).

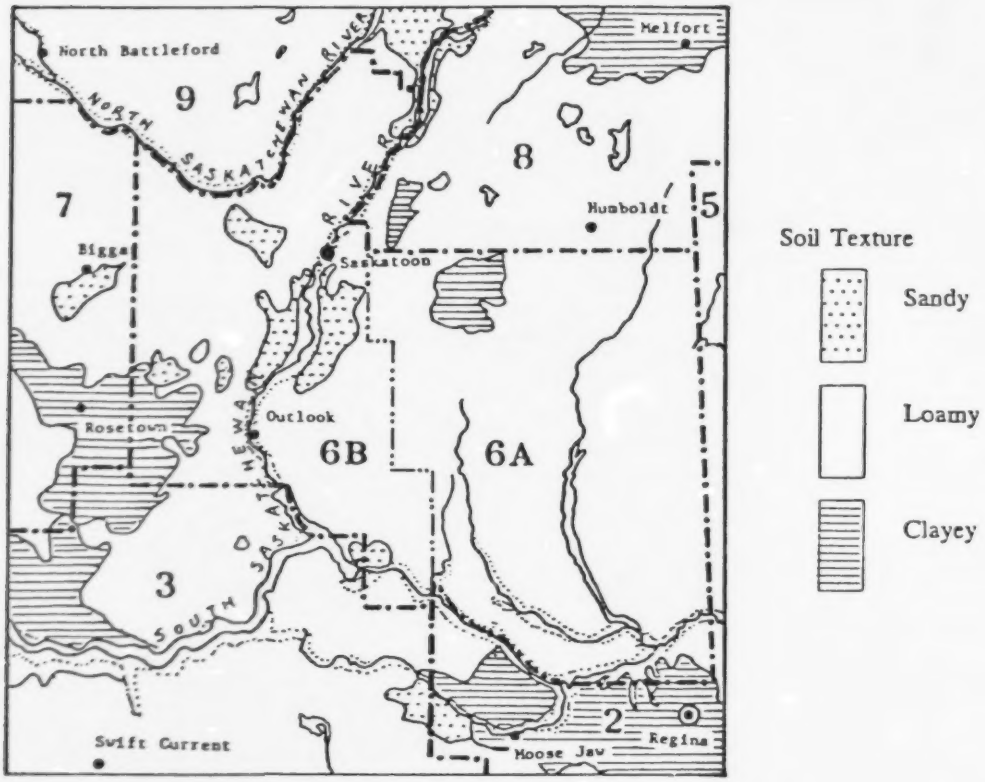
The miscellaneous parameters comprise: site and crop variety identifiers; site latitude; year; specifiers for amounts and dates of irrigation (if any), and desired frequency of printout of detailed soil-water and growth data tables (see Appendix C).

Figure 2 -- CERES Wheat Model



NOTES:
a. reads in parameter data.
b. reads in soils data.
c. reads in weather data.
d. all stages except 7.
e. stages 1 and 9 only.
f. all stages except 6.
g. stages 1 to 5 only.
h. stages 1 and 2 only.

Figure 3



SASKATCHEWAN

— CROP DISTRICT 6 —

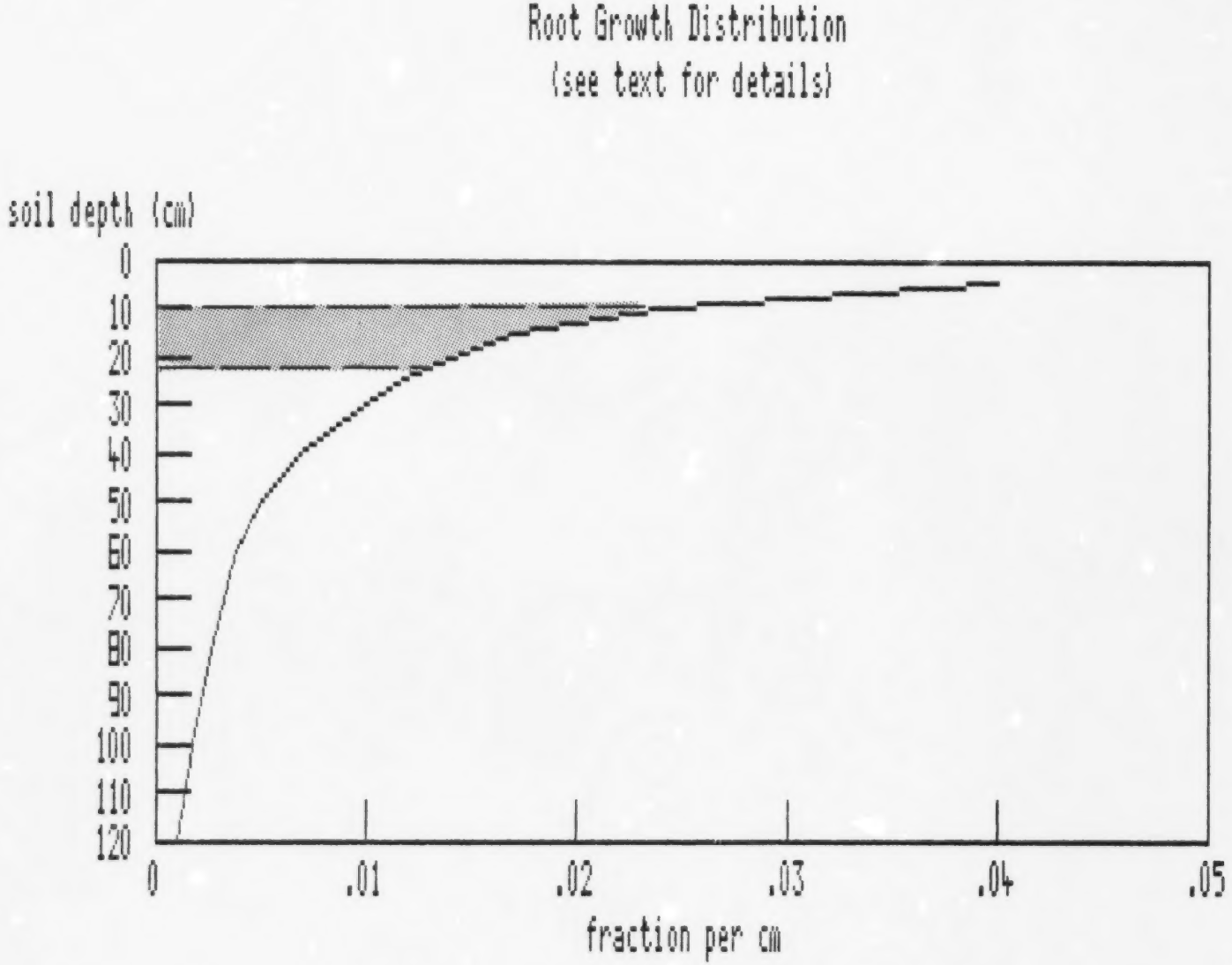
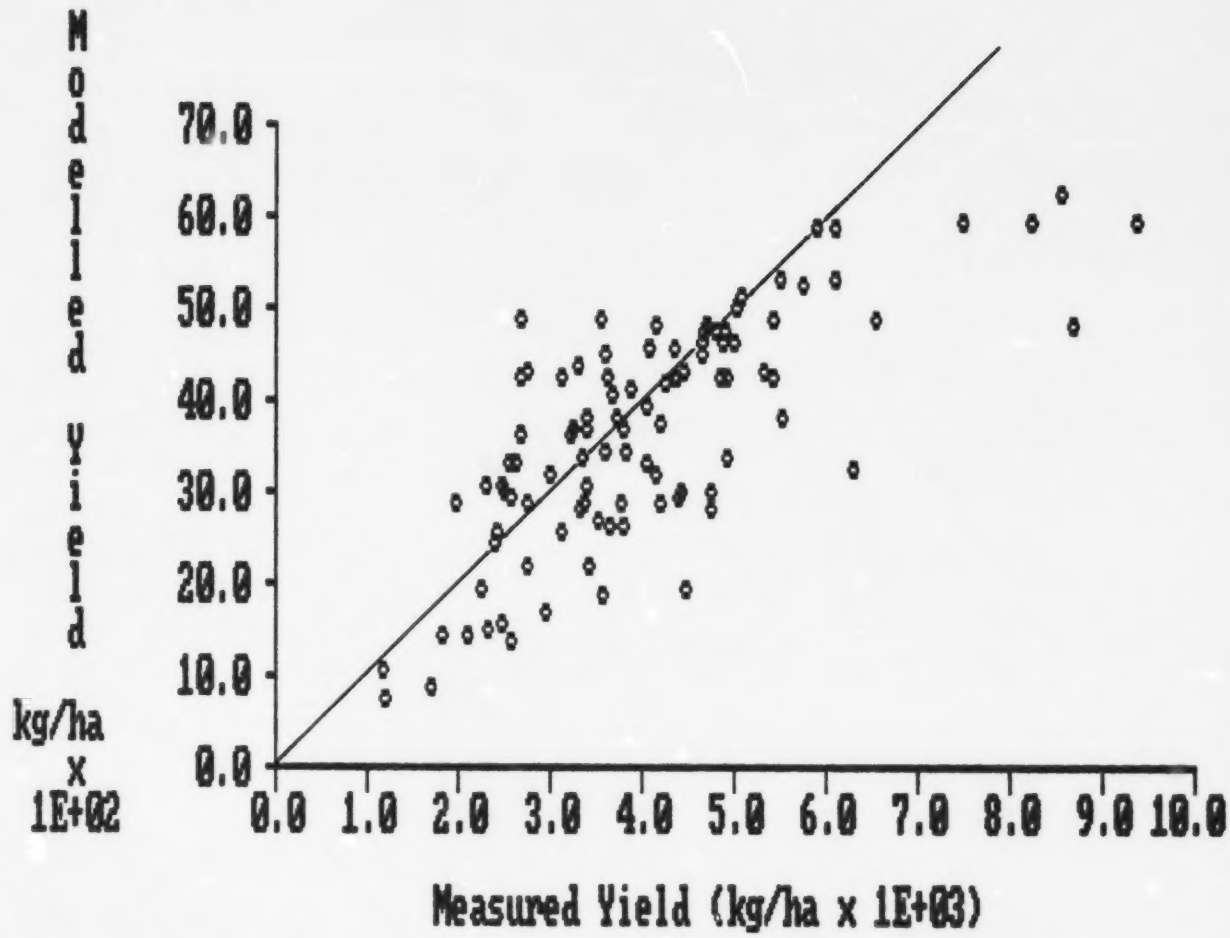

Root Growth Distribution
(see text for details)
soil depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
0
.01
.02
.03
.04
.05
fraction per cm

Figure 4

Figure 5



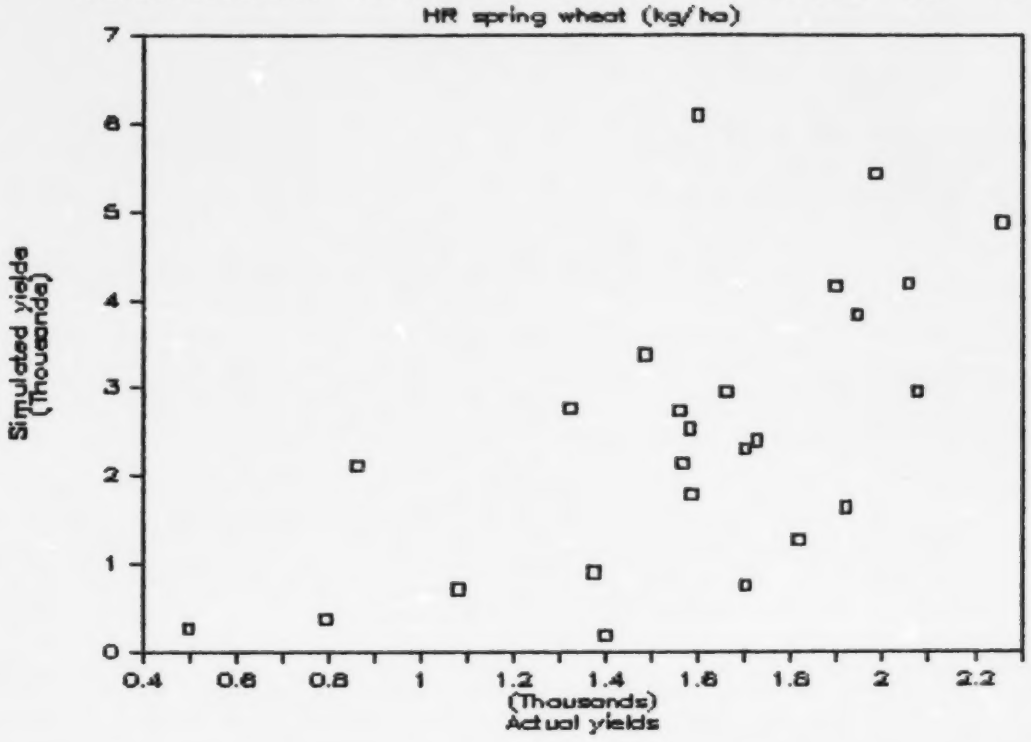
Comparison of CERES simulated yields with measured wheat yields for 99 runs from test sites around the world (Ritchie et al, unpublished data). The straight line shows the 1:1 relationship. The correlation coefficient is 0.74, and the linear regression lines are:

$$X = 648 + 0.928\ Y \qquad \text{(measured on modelled)}$$

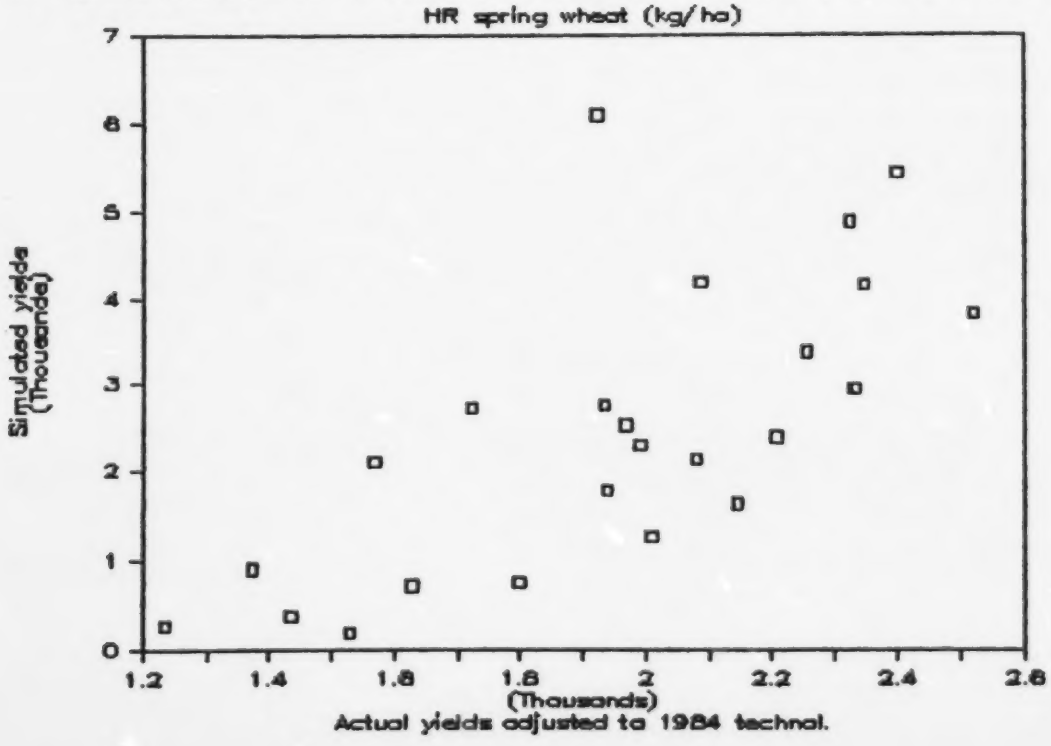
$$Y = 1250 + 0.595\ X \qquad \text{(modelled on measured)}$$

Figure 6

A - Saskatoon Wheat Yields — 1960 to 1984



B - Saskatoon Wheat Yields — 1960 to 1984



Saskatchewan Wheat Yields: 1916—1984

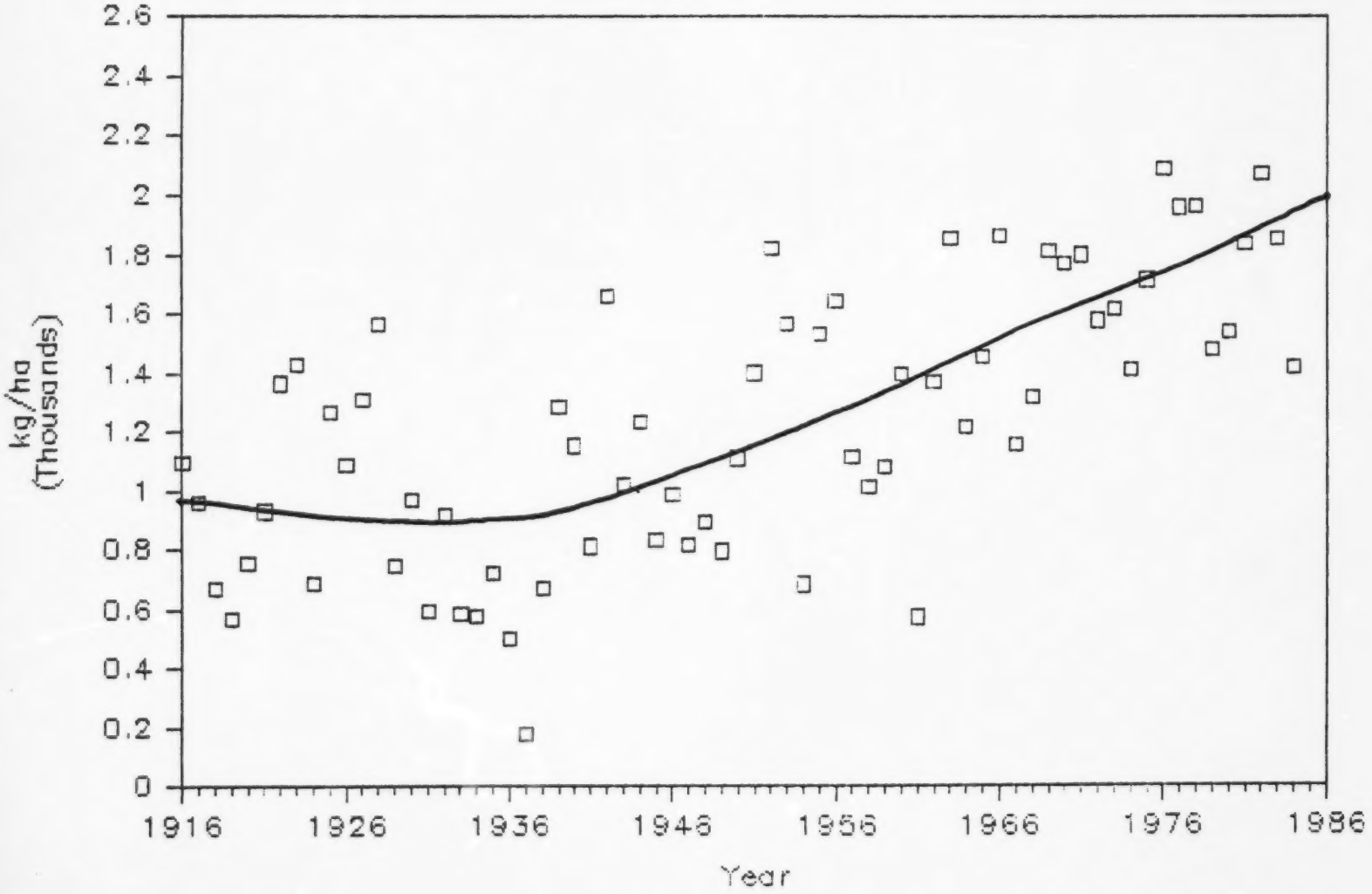


Figure 7

Appendix A

1951-80 Average Daily Saskatoon Weather Data As Used in CERES Model

year	Julian date	solar rad.	max. temp.	min. temp.	precip.
1999121	18.7	14.0	1.0		9.1
1999122	19.2	14.0	1.0		
1999123	18.3	15.0	1.0		
1999124	17.8	15.0	1.0		
1999125	15.2	15.0	1.0		
1999126	18.6	15.0	2.0		
1999127	19.2	15.0	2.0		
1999128	20.0	16.0	1.0		9.1
1999129	19.5	16.0	2.0		
1999130	20.6	16.0	2.0		
1999131	23.5	16.0	2.0		
1999132	21.1	18.0	3.0		
1999133	23.0	17.0	3.0		
1999134	20.9	17.0	3.0		
1999135	21.2	18.0	3.0		9.1
1999136	18.0	19.0	4.0		
1999137	13.9	19.0	4.0		
1999138	17.4	18.0	3.0		
1999139	15.4	18.0	3.0		
1999140	16.9	19.0	4.0		
1999141	20.0	19.0	5.0		
1999142	22.5	20.0	5.0		9.1
1999143	20.1	19.0	6.0		
1999144	19.1	20.0	6.0		
1999145	20.9	20.0	6.0		
1999146	22.6	20.0	6.0		
1999147	21.4	21.0	6.0		
1999148	19.3	21.0	6.0		
1999149	20.3	21.0	6.0	11.9	
1999150	21.9	21.0	7.0		
1999151	20.2	20.6	6.0		
1999152	22.0	20.0	6.0		
1999153	23.6	20.0	7.0		
1999154	17.5	20.0	7.0		
1999155	18.6	21.0	7.0		
1999156	19.3	20.0	8.0	14.0	
1999157	21.3	20.0	7.0		
1999158	22.0	21.0	7.0		
1999159	21.0	21.0	7.0		
1999160	24.3	22.0	8.0		
1999161	24.4	22.0	8.0		
1999162	22.2	22.0	8.0		
1999163	21.5	22.0	8.0	14.0	
1999164	20.1	22.0	8.0		
1999165	19.5	22.0	9.0		
1999166	22.8	23.0	9.0		
1999167	23.2	23.0	9.0		
1999168	21.3	23.0	10.0		
1999169	24.1	22.0	9.0		
1999170	22.4	22.0	8.0	14.0	
1999171	21.6	22.0	9.0		
1999172	20.1	23.0	9.0		
1999173	22.1	24.0	10.0		
1999174	20.5	23.0	10.0		
1999175	22.4	23.0	10.0		
1999176	22.1	23.0	10.0		
1999177	20.0	24.0	10.0	13.6	
1999178	19.9	22.0	10.0		
1999179	22.9	22.0	9.0		
1999180	25.5	22.0	10.0		
1999181	22.4	23.6	10.0		
1999182	23.0	23.0	10.0		
1999183	19.5	24.0	10.0		
1999184	21.7	24.0	11.0	12.6	
1999185	24.6	25.0	11.0		
1999186	21.5	25.0	12.0		
1999187	23.1	25.0	12.0		
1999188	21.1	25.0	12.0		
1999189	22.1	25.0	12.0		
1999190	25.5	26.0	11.0		
1999191	21.5	26.0	11.0	12.6	
1999192	24.0	26.0	13.0		
1999193	21.6	26.0	12.0		
1999194	18.2	25.0	12.0		
1999195	17.9	26.0	12.0		
1999196	19.8	26.0	12.0		
1999197	20.9	26.0	13.0		
1999198	23.9	26.0	11.0	12.6	
1999199	22.7	26.0	12.0		
1999200	21.9	27.0	12.0		
1999201	21.0	26.0	13.0		
1999202	22.4	27.0	12.0		
1999203	22.7	26.0	12.0		
1999204	21.0	27.0	12.0		
1999205	21.1	26.0	12.0	12.6	
1999206	24.0	26.0	12.0		
1999207	22.0	26.0	12.0		
1999208	21.7	27.0	11.0		
1999209	20.2	26.0	12.0		
1999210	19.4	25.0	11.0		
1999211	17.6	26.0	11.0		
1999212	19.0	26.0	12.0	8.4	
1999213	19.5	25.0	11.0		
1999214	18.8	25.0	10.0		
1999215	17.7	26.0	11.0		
1999216	19.0	27.0	12.0		
1999217	20.6	25.0	12.0		
1999218	19.8	25.0	11.0		
1999219	20.7	25.0	11.0	7.7	
1999220	16.9	25.0	11.0		
1999221	20.0	24.0	11.0		
1999222	20.5	25.0	10.0		
1999223	18.2	25.0	11.0		
1999224	17.3	25.0	11.0		
1999225	18.8	25.0	11.0		
1999226	20.4	25.0	10.0	7.7	
1999227	18.1	25.0	10.0		
1999228	17.7	25.0	10.0		
1999229	17.8	25.0	10.0		
1999231	17.5	25.0	10.0		
1999231	17.0	24.0	10.0		
1999232	15.4	24.0	10.0		
1999233	16.9	25.0	10.0	7.7	
1999234	18.1	25.0	10.0		
1999235	16.1	24.0	9.0		
1999236	14.7	24.0	10.0		
1999237	15.6	24.0	9.0		
1999238	19.4	23.0	8.0		
1999239	16.9	24.0	9.0		
1999240	16.4	22.0	9.0	7.7	
1999241	16.6	23.0	8.0		
1999242	14.6	23.0	8.0		
1999243	14.5	23.0	8.0		
1999244	13.5	21.0	8.0		
1999245	13.0	21.0	7.0		
1999246	16.1	21.0	7.0		
1999247	13.3	22.0	7.0	7.7	
1999248	10.2	20.0	7.0		
1999249	12.7	20.0	6.0		
1999250	13.2	21.0	6.0		
1999251	13.6	20.0	6.0		
1999252	13.7	19.0	6.0		
1999253	13.7	19.0	6.0		
1999254	13.5	20.0	6.0	7.7	
1999255	9.4	19.0	6.0		
1999256	12.1	18.0	6.0		
1999257	14.5	18.0	5.0		
1999258	12.4	18.0	4.0		
1999259	11.7	18.0	4.0		
1999260	10.9	18.0	3.0		
1999261	12.2	18.0	4.0	7.7	
1999262	11.5	18.0	4.0		
1999263	12.5	16.0	3.0		
1999264	12.0	16.0	3.0		
1999265	13.1	16.0	3.0		
1999266	12.5	16.0	3.0		
1999267	9.5	15.0	2.0		
1999268	10.8	15.0	2.0	6.6	
1999269	9.4	14.0	2.0		
1999270	10.2	14.0	2.0		
1999271	9.9	15.0	1.0		
1999272	10.2	15.0	1.0		
1999273	9.6	15.0	1.0		

CERES Model--Soils data files for use with mean weather data.

(Format of first line is: Year; No. of layers; Soil albedo; Upper limit of soil evaporation in mm/day; SWCON; CN2. Second and following lines have format of: layer thickness in cm; lower limit, drained upper limit, saturated water content, and initial soil water content of each layer, all in volume fraction; and weighting factor for root growth).

```
Asquith:
1999 5 0.14  6.00  0.50 60.0
    10 0.091 0.174 0.350 0.143  0.400
    12 0.085 0.150 0.350 0.137  0.200
    20 0.094 0.163 0.350 0.146  0.200
    20 0.097 0.171 0.350 0.149  0.100
    58 0.116 0.202 0.350 0.168  0.100

Bradwell:
1999 5 0.14  6.00  0.50 60.0
    15 0.170 0.290 0.350 0.220  0.446
    25 0.160 0.280 0.350 0.210  0.304
    53 0.170 0.290 0.350 0.220  0.214
    13 0.186 0.325 0.350 0.238  0.018
    14 0.206 0.361 0.370 0.258  0.018

Elstow:
1999 5 0.14  6.00  0.50 60.0
    38 0.190 0.330 0.400 0.256  0.714
    10 0.200 0.360 0.400 0.266  0.089
    12 0.210 0.370 0.400 0.276  0.054
    10 0.250 0.430 0.450 0.316  0.036
    50 0.260 0.460 0.470 0.326  0.107

Weyburn:
1999 5 0.14  6.00  0.50 60.0
    18 0.186 0.320 0.350 0.252  0.536
    22 0.170 0.299 0.350 0.236  0.250
    18 0.178 0.310 0.350 0.244  0.107
    34 0.172 0.301 0.350 0.238  0.089
    28 0.173 0.298 0.350 0.239  0.018

Sutherland:
1999 5 0.14  6.00  0.50 60.0
    27 0.320 0.500 0.550 0.393  0.634
    18 0.340 0.550 0.600 0.413  0.161
    20 0.330 0.550 0.600 0.403  0.089
    25 0.350 0.570 0.600 0.423  0.071
    30 0.360 0.580 0.600 0.433  0.045

Sceptre:
1999 5 0.14  6.00  0.50 60.0
     7 0.410 0.610 0.630 0.483  0.268
    20 0.430 0.670 0.690 0.503  0.375
    23 0.430 0.690 0.710 0.503  0.179
    20 0.450 0.730 0.750 0.523  0.071
    50 0.470 0.750 0.770 0.543  0.107
```

```
NNN  NSLAY  SALB  U  SWCON  CN2
     DLAYR   LL   DUL   SAT   SW   WR
                  "
                  "
                  "
                  "
```

==========

Typical values of soils parameters that have been used elsewhere: (from CERES soils file)

SWCON	0.1	loam
	0.3	silt loam, silty clay
	0.5	most others
	0.6	sand
SALB	0.09	
	0.12	
	0.14	
U	5	few
	6	most
	7,8	few
	12,13	desert
	18	lysimeters
CN2	55	few
	60	most
	76	few
WR	totals range from 1.6 to 3.3 with the majority near 2.0	

Input Format of Crop and Miscellaneous Parameter Data

```
LOCATION    IVARTY    LAT    YEAR    ISOW    PLANTS    SDEPTH    U
   A10   1X   I3   1X  F4 1X  I2  1X  I3  1X   F4   1X   F4  1X F4 1X

PHINT   P1D    P1V    P5    G2    G3    G4  KOUTWA  KOUTGR  IIRR  IQUIT
 F4  1X  F4 1X  F4 1X F4 1X F4 1X F4 1X F4    I1      I1      I1     I1

*********************************************************************************************

Saskatoon  101 52.2 60 125 250. 5.00  6.0  75. .003 .006 500.  25. 1.50 1.007700

*********************************************************************************************
```

Description of Input Parameter Data----------

LOCATION	--	description of dataset (A10)
IVARTY	---	numerical descriptor for variety (I3)
LAT	----	site latitude (F4)
YEAR	----	year for run (pointer to soil & weather datafiles) (I2)
ISOW	----	Julian date of sowing (I3)
PLANTS	---	planting density (F4)
SDEPTH	---	planting depth (F4)
U	----	upper limit on phase 1 soil evaporation (F4)
PHINT	----	phyllochron interval (F4)
P1D	----	daylength sensitivity (F4)
P1V	----	vernalization sensitivity (F4)
P5	----	degree-day requirement for phase 5 (F4)
G2	----	no. of grains per spike (F4)
G3	----	grain fill rate (F4)
G4	----	tiller stem weight (F4)
KOUTWA	---	frequency of water-use data printout (I1)
KOUTGR	---	frequency of growth data printout (I1)
IIRR	----	irrigation data indicator (0 - none) (I1)
IQUIT	----	value of 9 indicates final parameter data line (I1)

The bracketted characters refer to the FORTRAN format fields.
For example, A10 indicates an alpha-numeric field of 10 characters;
I3 is an integer field of 3 characters length; and F4 is a decimal
number field of 4 characters length. See Appendix F for label codes.

Appendix D

LOCATION: SASKATOON; VARIETY NUMBER: 101

GENETIC PARAMETERS: P1D = .006 P1V = .0030 P5= 500. G1 = 1.00 G2 = 25.00 G3 = 1.50 G4 = 1.00 G5 = 1.00

OTHER PARAMETERS: ISOW=134; PLANTS=250.; KOUTWA= 9; KOUTGR= 9; SDEPTH= 5.0; LAT=52.2; IQUIT=0; PHINT=65.0; IIRR=0

SOIL PARAMETERS:ALBEDO= .14 U= 6.0 SWCON= .50 RUNOFF CURVE NO.= 60.0 SOIL NO.= 99 NO. OF LAYERS= 5

THE PROGRAM STARTED ON JULIAN DAY 121

DATE	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	CSD2	WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION ET	ES	EP	PREC	PESW
14/ 5/99	134	0.	SOWING									
15/ 5/99	135	8.	GERMINATION					22.0	22.0	.0	18.2	8.4
25/ 5/99	145	96.	EMERGENCE, PHINT = 65.					12.6	12.6	.0	18.2	8.1
16/ 6/99	167	400.	TERM SPIKELET, VERN DAYS=11.	60.	1.02	.01	.05	66.4	50.4	16.0	58.1	6.7
29/ 6/99	180	610.	END VEG BEGIN EAR GROWTH	253.	2.72	.28	.43	111.7	70.8	40.9	85.7	4.9
6/ 7/99	187	730.	END EAR GROWTH,EARS= 639.	346.	2.28	.51	.63	132.8	81.2	51.7	98.3	4.1
17/ 7/99	198	937.	BEGIN GRAIN FILL,GPSM= 6924.	424.	1.55	.67	.78	160.3	97.4	62.9	110.9	3.6
14/ 8/99	226	1430.	MATURITY,GRAIN WT = .0273	509.	.19	.75	.83	209.5	133.0	76.5	152.2	2.0

YIELD = 1888. KG/HA

CROP MATURE FOR SINGLE YEAR RUN
Stop - Program terminated.

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 15.	.170	.290	.350	.120	.236	.446
15.- 40.	.160	.280	.350	.120	.226	.384
40.- 93.	.170	.290	.350	.120	.236	.214
93.- 106.	.186	.325	.350	.139	.252	.018
106.- 120.	.206	.361	.370	.155	.272	.018

Detailed Soil Water Information

DAY	JUL DAY	AVERAGE ES	EP	ET	EO	SR	MAX	MIN	PERIOD RUNOFF	DRAIN	PREC	SOIL WATER CONTENT WITH DEPTH SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	TOTAL PESW
9/ 5/99	129	1.5	.0	1.5	3.3	442.	15.0	1.3	.00	.00	18.20	.26	.23	.24	.25	.27	.00	.00	.00	.00	.00	8.4
18/ 5/99	138	1.3	.0	1.3	3.8	477.	17.6	3.0	.00	.00	9.10	.24	.23	.24	.25	.27	.00	.00	.00	.00	.00	8.1
27/ 5/99	147	1.2	.0	1.2	4.0	475.	19.6	5.2	.00	.00	9.10	.23	.23	.24	.25	.27	.00	.00	.00	.00	.00	8.0
5/ 6/99	156	1.7	.2	1.9	4.2	485.	20.5	6.7	.00	.00	25.90	.27	.24	.24	.25	.27	.00	.00	.00	.00	.00	8.9
14/ 6/99	165	2.1	1.0	3.1	4.5	521.	21.6	7.8	.00	.00	14.00	.22	.22	.24	.25	.27	.00	.00	.00	.00	.00	7.5
23/ 6/99	174	1.6	2.0	3.7	4.5	526.	22.8	9.2	.00	.00	14.00	.17	.19	.22	.25	.27	.00	.00	.00	.00	.00	5.6
2/ 7/99	183	1.4	1.7	3.0	4.4	525.	23.0	9.9	.00	.00	13.60	.15	.18	.21	.25	.27	.00	.00	.00	.00	.00	4.2
11/ 7/99	192	1.6	1.4	3.1	5.1	545.	25.2	11.7	.00	.00	25.20	.18	.17	.20	.24	.27	.00	.00	.00	.00	.00	3.8
20/ 7/99	201	1.6	.8	2.4	4.8	499.	26.0	12.1	.00	.00	12.60	.16	.17	.20	.24	.26	.00	.00	.00	.00	.00	2.8
29/ 7/99	210	1.4	.7	2.1	4.7	514.	26.2	11.8	.00	.00	12.60	.14	.16	.19	.23	.26	.00	.00	.00	.00	.00	2.1
7/ 8/99	219	1.0	.4	1.4	4.0	459.	25.6	11.2	.00	.00	16.10	.18	.16	.19	.23	.25	.00	.00	.00	.00	.00	2.3
16/ 8/99	228	1.3	.2	1.5	3.7	446.	24.9	10.6	.00	.00	7.70	.14	.16	.19	.23	.25	.00	.00	.00	.00	.00	1.6
25/ 8/99	237	.4	.0	.4	3.8	396.	24.4	9.8	.00	.00	7.70	.14	.16	.19	.23	.25	.00	.00	.00	.00	.00	1.6
3/ 9/99	246	.8	.0	.8	3.3	372.	22.3	8.0	.00	.00	7.70	.14	.16	.19	.23	.25	.00	.00	.00	.00	.00	1.6
12/ 9/99	255	1.1	.0	1.1	2.6	301.	20.0	6.2	.00	.00	15.40	.17	.16	.19	.23	.25	.00	.00	.00	.00	.00	2.1
21/ 9/99	264	.9	.0	.9	2.4	292.	17.6	4.0	.00	.00	7.70	.17	.16	.19	.23	.25	.00	.00	.00	.00	.00	2.0
30/ 9/99	273	.9	.0	.9	1.9	253.	15.0	1.9	.00	.00	6.60	.16	.16	.19	.23	.25	.00	.00	.00	.00	.00	1.9

Detailed Crop Growth Information

DATE	JUL DAY	BIO MASS	TILL /SM.	LAI	SUMDTT	TRWU	PSW	ROOT WT	STEM WT	GRAIN WT	LEAF WT	SEN LFA	SW DF1	SW DF2	ROOT DPTH	PTF	ROOT LENGTH VOLUME L1	L2	L3	L4	L5	L6	L7	L8
2/ 6/99	153	5.	250.	.07	115.	.04	6.4	.010	.000	.000	.019	0.	1.0	.9	37.	.56	.1	.0	.0	.0	.0	.0	.0	.0
11/ 6/99	162	29.	609.	.47	243.	.14	6.0	.048	.000	.000	.115	0.	1.0	.9	65.	.56	.5	.2	.0	.0	.0	.0	.0	.0
20/ 6/99	171	128.	888.	1.68	63.	.49	.3	.119	.052	.000	.462	4.	.9	.8	96.	.81	1.3	.6	.1	.0	.0	.0	.0	.0
29/ 6/99	180	267.	911.	2.65	15.	.15	.4	.169	.402	.000	.665	16.	.7	.5	120.	.98	1.7	.9	.2	.0	.0	.0	.0	.0
8/ 7/99	189	369.	639.	2.85	44.	.09	.6	.184	.852	.000	.624	40.	.4	.3	120.	.98	1.8	1.0	.3	.1	.0	.0	.0	.0
17/ 7/99	198	436.	639.	1.52	14.	.16	.6	.190	1.026	.131	.585	61.	.3	.2	120.	.91	1.8	1.0	.3	.1	.1	.0	.0	.0
26/ 7/99	207	476.	639.	1.09	178.	.05	.6	.188	.894	.445	.566	78.	.3	.2	120.	.94	1.7	1.0	.3	.1	.1	.0	.0	.0
4/ 8/99	216	496.	639.	.76	336.	.03	.6	.181	.747	.698	.549	92.	.2	.1	120.	1.00	1.7	.9	.3	.1	.1	.0	.0	.0
13/ 8/99	225	509.	639.	.19	489.	.03	.6	.173	.747	.755	.532	115.	.2	.1	120.	1.00	1.7	.9	.3	.1	.1	.0	.0	.0

Plant Genetic Parameters	Used
PHINT -- the phyllochron interval, or number of degree days between the appearance of successive leaves	65
P1D -- daylength sensitivity, used to calculate the daylength factor, DF = 1 - P1D*(20 - HRLT)^2 where HRLT is the daylength	.006
P1V -- vernalization sensitivity, used to calculate the vernalization factor, VF = 1 - P1V*(50 - CUMVD) where CUMVD is cumulative vernalization days	.003
P2 -- degree days between terminal spikelet and end of vegetative growth; set at 3 phyllochron intervals	(= 3*PHINT)
P3 -- degree days between end of vegetative growth and end of pre-anthesis elongation growth; set at 2 phyllochron units	(= 2*PHINT)
P4 -- degree days between end of pre-anthesis ear growth and beginning of grain fill; set at 200	
P5 -- degree days between beginning of grain fill and maturity	500
P9 -- degree days from germination to emergence; set as a function of seeding depth: P9 = 40 + 10.2*SDEPTH	
G1 -- rate of vegetative expansion growth; set at 1.0	
G2 -- number of grains per spike	25
G3 -- grain-fill rate (mg/day)	1.5
G4 -- tiller stem weight (g)	1.0
G5 -- relative winter hardiness; set at 1.0	

Phenological Stages Used in the CERES Model

Stage	Description	Thermal time factor
8	sowing to germination	P8
9	to emergence	P9 (=40+10.2*SDEPTH)
1	to terminal spikelet	P1
2	to end of vegetative growth	P2 (=3*PHINT)
3	to end of pre-anthesis ear growth	P3 (=2*PHINT)
4	to beginning of grain fill	P4 (=200)
5	to physiological maturity	P5
6	to harvest	
7	to sowing	

P8 is dependent on sufficient soil moisture in the top 2 soil layers.

P1 is taken as the lesser of vernalization and daylength requirements. The degree-day base temperature is 0°C for stages 1 to 4; 1°C for stages 5 and 6; and 2°C for stages 7 to 9.

Crop data other than genetic required to run or validate model

Depth of seeding--(G) 4-5 cm recommended for wheat

(A) experiments using depths from 5 to 10 cm usually gave highest yields for shallowest depths.

Date of seeding-- (G) May 1 to June 1; Indian Head study showed highest yield for May 1, decreasing .25 to .5 % per day thereafter.

(A) 21 year U of S study used earliest seeding dates from 6 April to 4 May, averaging 18 April, along with later dates. Highest yields were obtained from mid-May seedings on average. Delayed seeding resulted in delayed maturity. All seedings during May had similar yields. Studies elsewhere in the province showed higher yields for earlier plantings. Actual mean seeding dates may be found in Agricultural Statistics (Anonymous, 1980; etc).

Seeding density-- (G) recommended rates for wheat are 45-75 kg/ha on brown soils and dark brown sandy to clay loam soils; on dark brown clays, black, gray-black and gray soils the rates are 60 -105 kg/ha. Wheat seeds have an average density of about 770 kg/m3.

(A) recommend lighter seeding rates, particularly in dry years. Results from a number of studies are shown, e.g. Regina -- 14 kg/ha gave 2190 kg and 28 kg/ha gave 2840 kg/ha. At Swift Current there was a decrease of yield with seeding rates above 22 kg/ha, while at Melfort yields increased about one-third as seeding rate rose from 67 to 168 kg/ha.

Seed weight-- (A) approximately 30 mg. Thus at 70 kg/ha seeding density there would be 7000/30 = 233 seeds m^{-2}.

Sources of data: (G) -- Guide to Farm Practice in Saskatchewan (G), (Anonymous; 1984).

(A) -- Principles of Agronomy (A) (Austenson; 1979).

```
**************************************************************************
*                          LABEL DIRECTORY                               *
**************************************************************************
```

CN2 --parameter specifying soil runoff characteristics

DLAYR --thickness of a soil layer

DUL --drained upper limit of available soil water

G1 --rate of vegetative expansion growth during phase 1

G2 --number of grains per spike

G3 --grain-fill rate (mg/day)

G4 --tiller stem weight (g)

G5 --relative winter hardiness

IIRR --when =0, signals no irrigation applied

IQUIT --when =9, signals end of job

ISOW --sowing date (Julian date)

IVARTY --crop variety identification number

KOUTGR --period (d) between desired growth data print-outs (0 indicates nil)

KOUTWA --period (d) between desired water-balance data print-outs (0 indicates nil)

LAT --site latitude

LL --lower limit of availability of soil water

NNN --soil data year identifier

NSLAY --number of soil layers

P1D --daylength sensitivity coefficient

P1V --vernalization sensitivity coefficient

P2 --thermal time from terminal spikelet to end of vegetative growth

P3 --thermal time from end of vegetative growth to end of pre-anthesis ear growth

P4 --thermal time from end of pre-anthesis ear growth to beginning of grain fill

P5 --thermal time from beginning of grain fill to maturity

P9 --thermal time from germination to emergence

PHINT --phyllochron interval (deg.days)

PLANTS --planting density (no. per m^2)

SALB --soil albedo

SAT --saturated soil water content (vol.fract.)

SDEPTH --seeding depth (cm)

SW --initail soil water content

SWCON --factor for calculating soil drainage

U --upper limit of soil evaporation (mm/day)

WR --weighting factor for new root growth

ACKNOWLEDGEMENTS

This work was supported in part by research grants provided by the Sasskatchewan Research Council and by the College of Agriculture Hantelman Trust of the University of Saskatchewan.